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ABSTRACT

The Mirror Fusion Test Facility (MFTF), currently being constructed at the Lawrence Livermore Laboratory, has large superconducting magnets, cryopanels, and supporting cryogenic equipment that will comprise one of the world's largest liquid helium (LHe) systems. The facility will provide mirror magnetic confinement for experimental fusion plasmas that will be approximately the same physical size as if in a conceptual fusion reactor. The cryogenic system typifies the magnitude and makeup of systems that will be used in future magnetic fusion reactors. Here we describe the LHe cryopumping and magnet systems. Principal components include a 3300 W helium refrigerator, 30,000 L LHe storage, a 1.5 MW (2000 hp) refrigerator compressor, 1100 m^2 of cryopanels, and a 420 MJ superconducting magnet system. Design features, method of operation, thermal protection, and helium recovery operations are discussed in this paper.

INTRODUCTION

Less than two decades ago, the largest liquid helium (LHe) system had only a few hundred liters of LHe and less than a hundred watts refrigeration capacity. The Mirror Fusion Test Facility (MFTF), which is presently under construction at Lawrence Livermore Laboratory, will have a LHe system capacity of 30,000 L, a liquefaction rate of 600 L/h, or 3300 W refrigeration capacity. This system will be one of the world's largest and will demonstrate the advancement of cryogenic technology.

Historically, controlled fusion research has progressed in parallel with LHe technology development. Magnetic confinement of fusion plasmas require high-strength magnetic fields that are best generated by superconducting magnets. Moreover, very low chamber pressures are required to inhibit contamination of plasmas and are best achieved with LHe cryopumps in conjunction with suitable getters. As fusion experiments get larger, so do the required supporting LHe systems. Future fusion power reactors will also require larger LHe systems. It is thus evident that magnetic fusion research is having a significant impact on cryogenic technology.

The MFTF is a fusion research project that includes a 300-t (660,000-lb) yin-yang pair of superconducting magnets and 1100 m^2 of LHe cryopumping surfaces contained in an 18-m-long, 12-m-diameter horizontal vacuum vessel illustrated in Fig. 1. The magnets will generate a 2-T central field and the cryosurfaces will develop a 40-mPa (3-μTorr) operating pressure for experimental fusion plasmas. A plasma fan of ionized deuterium will stream between the magnet lobes along the horizontal axis of the vacuum chamber, and beams of neutral D^+ ions will be injected vertically and horizontally between the magnets into the plasma center creating a 50-keV-average beam energy. Scheduled startup of the project is late 1980.

In this paper we describe only the LHe cryogenic system for the MFTF. Even though the supporting liquid nitrogen (LN) system capacity is more than 150,000 L and 100 kW, it is considered a conventional technology and is not reviewed here. The subsystems we describe are the refrigerator, cryopanel, magnet, and recovery subsystems.

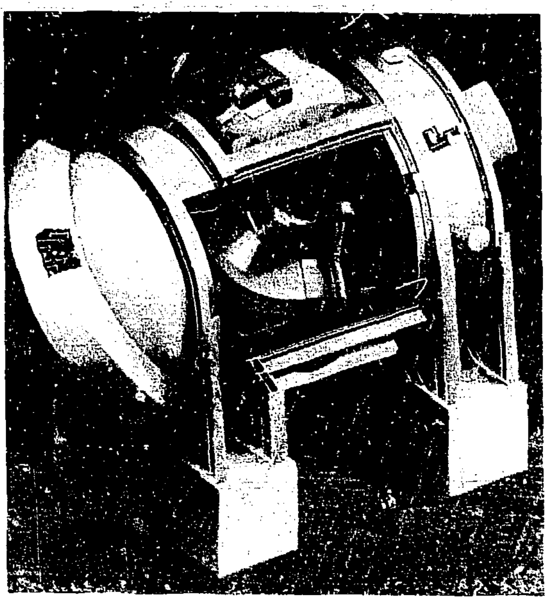

Fig.1 The MFTF vacuum vessel and magnets

THE CRYOGENIC SYSTEM

The LHe facility depicted in Fig. 2 includes a refrigerator, compressor, surge tank, Joule-Thompson (JT) valve, storage and supply Dewars, magnets, and associated piping. All lines and components are vacuum jacketed and shielded with LN-cooled surfaces to reduce thermal radiation. (Since radiation heat transfer is proportional to the fourth power of the source temperature, LN surfaces emit less than 0.5% of the heat that room temperature surfaces would.)

The 25,000-L storage Dewar provides a standby source of LHe in the event that maintenance is required on the refrigerator. This Dewar also provides storage for LHe removed from the cryopanels and magnet.

The two supply Dewars are ballast and phase separators for the cryopanel and magnet systems. These two systems are designed so they can be operated independently.

During steady state operation, helium is liquefied in the storage Dewar and then transferred on demand to each supply Dewar at 4.35 K. Cold gas is returned to

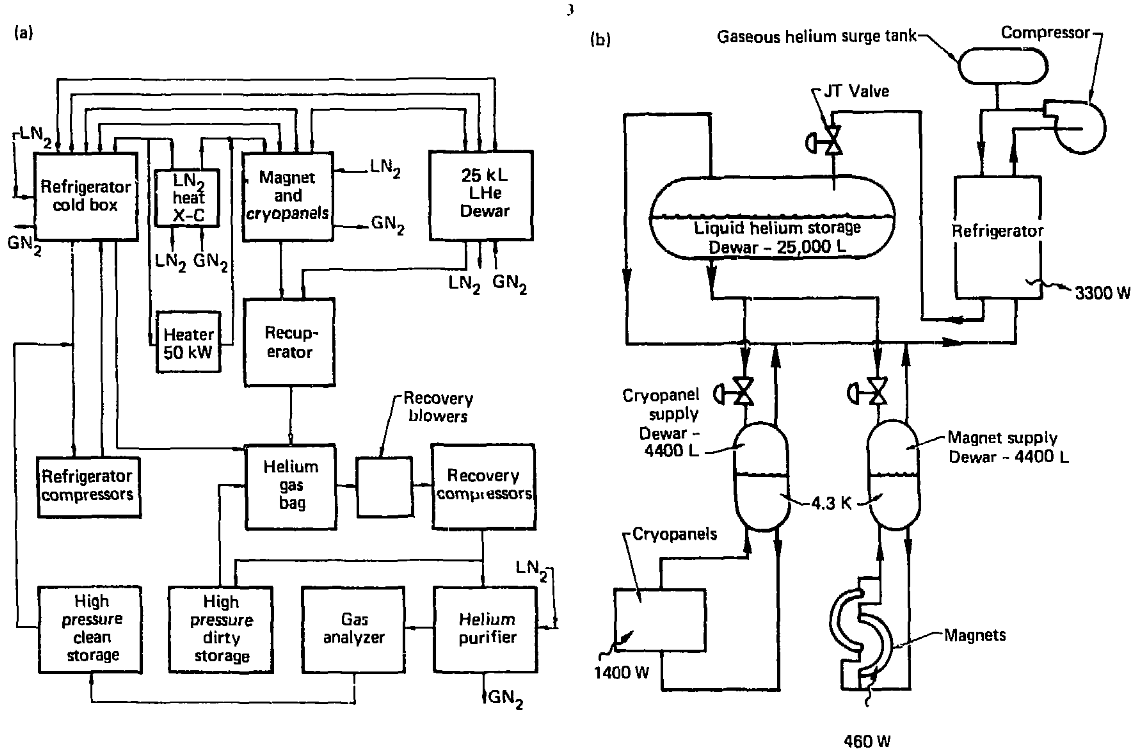

Fig.2 Helium cryosystem schematic; (a) overall system; (b) primary components

the refrigerator from all three Dewars to maintain closed loop operation.

Liquid helium flow from the supply Dewars to the magnet or cryopanels is by natural convection. The Dewars are located about 15 m above the magnet and cryopanel inlets. Heat loads in the cryopanels and magnets create helium vapor that reduces bulk fluid density in the return pipes and causes LHe flow. This natural convective process is self-regulating because an increased heat load on the magnets or cryopanels increases flow. A high degree of reliability is inherent in this system since no mechanical pump is used.

HELIUM REFRIGERATION

The heart of the cryogenic system is the refrigerator: a machine capable of supplying 3300 W at 4.35 K. It operates on a Claude or reverse Brayton helium cycle in two modes: to build up LHe reserves and supply LHe for steady state heat loads. The LHe evaporated by the heat loads is returned to the refrigerator at a rate equal to the rate liquid is generated by the refrigerator. Figure 3 is a schematic of the refrigerator-compressor system. Room temperature helium enters the top of the refrigerator at 12 atm (1.2 MPa). Heat is first extracted from the helium in the LN heat exchanger where its temperature is reduced to about 80 K. Additional heat extraction occurs across two turbines by a thermodynamic work expansion process. A brake wheel on the same shaft as the turbine dissipates the energy and transfers it to room temperature helium in a separate coolant loop. (The turbines are approximately 4 cm in diameter and operate up to 5000 rps.) During steady state operation, the upper turbine discharge is about 24 K and the lower one about 7 K. Care is taken to ensure that

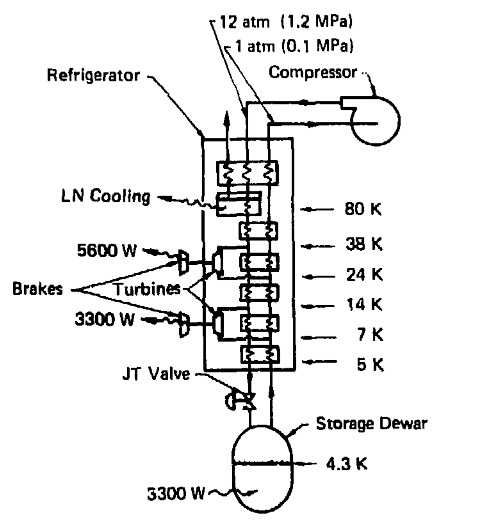

Fig.3 Schematic of the refrigerator-compressor system

temperatures in the refrigerator are above helium critical temperature (5.2 K) to prevent liquid formation in the turbines.

Final temperature reduction of the flow stream is by expansion in the JT valve outside the refrigerator. This adiabatic expansion of helium from 12 to 1 atm (1.2 to 0.1 MPa) results in a saturated mixture of vapor and liquid. The liquid drops into the Dewar and the vapor returns to the bottom of the refrigerator. The return helium flows up through the refrigerator where it is warmed to near room temperature by the downward helium stream. From there the flow returns to the compressor, thereby completing the cycle. Figure 4 shows the temperature-entropy diagram for the refrigerator-compressor system.

The MFTF refrigerator-compressor system specifications are given in Table 1.

CRYOPANEL SYSTEM

The cryopanels will provide an operating pressure of 40 mPa (3 μTorr) in the plasma chamber while absorbing on their 4.5 K LHe-cooled surfaces a large gas load from the plasma, neutral beams, outgassing, and normal leakage. A base pressure of approximately 1.3 μPa (10 nTorr) will be developed before each experimental run by two large external cryosorption pumps cooled to 2.8 K. Surfaces near the plasma center will receive a fresh coating of titanium before each experimental run to remove gas atoms in that region. These vacuum systems are backed by a large external rough vacuum pumping system described in Ref. 1.

Particulars of the MFTF cryopanel array are given in Table 2. The cryopanels are manifolded in banks. There are eight horizontal banks positioned parallel to the vessel centerline, and ten banks at 45 deg positioned parallel to the plasma surface near each end dome of the vessel. The cryopanel manifolding and layout is shown in Fig. 5.

The LHe-cooled surfaces of the cryopanels are bright finished and shielded from room temperature radiation by LN-cooled surfaces as shown in Fig. 6. The "Z-shaped," extruded LN-cooled shields provide "line-of-sight" closure of the cryopanels and ample

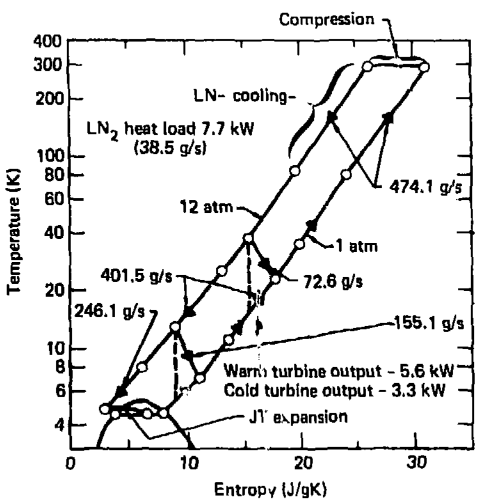

Fig.4 Temperature-entropy diagram for the refrigerator-compressor system

Table 1 MFTF refrigerator-compressor specifications

Compressor	
Type	Oil-flooded rotary screw, 2 first stages, 1 second stage
Manufacturer	Mycom,* Japan
Power	1.5 MW (2000 hp)
Skid size	7.3-m long × 4.0-m wide × 3.4-m high (controls not included)
Capacity	0.5 kg/sec (helium)
Pressure	1 atm abs (0.1 MPa) inlet, 12 atm abs (1.2 MPa) discharge
Refrigerator	
Type	Claude cycle, 7 counterflow heat exchangers, 2 turbines
Manufacturer	CVI Corporation, Columbus, Ohio
Size	Approximately 3.4-m diameter, 6.1-m high
Capacity	3300 W at 4.35 K as refrigerator, 600 L/h as liquifier
Turbines	Manufacturer: L'Aire Liquide, France
	Warm turbine: 5.6 kW, 38 K in, 24 K out, 73 g/s, 65% efficiency
	Cold turbine: 3.3 kW, 13 K in, 7 K out, 155 g/s, 65% efficiency

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Table 2 MFTF cryopanel specifications

Type	Integrally extruded aluminum tube and fins, welded tubing end connections
Manufacturer	CVI Corp, Columbus, Ohio
Operating temperature	4.5 K
Total area	1100 m^2 (frontal entrance area)
Total heat load	1400 W (primarily due to radiation heating)
Thermal shielding	Liquid-nitrogen-cooled "Z-panels" - 85 K
Pumping speed	100 ML/s (H_2 and D_2)

access for gas molecules to flow to the helium surfaces. These LN surfaces are coated with a thermal absorbing black paint to reduce heat radiation reflection onto the LHe-cooled surfaces.

THE MAGNET SYSTEM

The magnets must be sufficiently cooled with LHe to provide cryostability for the superconductors. This is achieved by assuring adequate flow and heat transfer around the magnets and providing strategically located plenums for inhibiting vapor build-up.

A schematic of the LHe system shown in Fig. 7, illustrates the lengths, bends, and altitudes of the transfer lines, the Dewar, and the magnets. Note that the magnet inlets and outlets are approximately 16 and 9 m, respectively, below the LHe Dewar. This configuration permits thermosiphon flow between the magnet and Dewar.

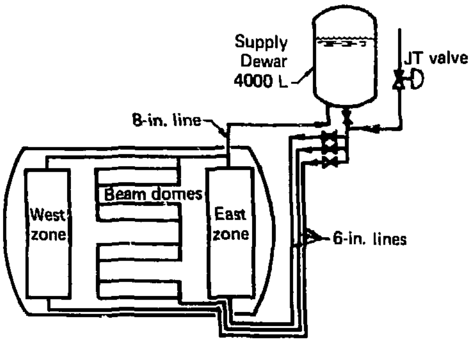

Fig.5 Cryopanel manifold schematic

The planes of symmetry of the magnets are oriented at 45 deg for the most effective LHe convection. Helium is supplied to the lowest point of each coil and an outlet line is connected at the highest point. The LHe flow divides between these two points, a portion going through each half of a coil.

Helium flow rate and quality related to heat load and flow system configuration were estimated by a finite difference analysis of a flow model(2). An iterative method was employed so that the results would reflect variable properties and two-phase flow effects. Cumulative contributions of friction, momentum, and gravity to steady-state flow were included. Piping pressure loss was found to be more than 10 times the magnet pressure loss.

Based on the flow analysis, a selected pipe size for the transfer lines is 6-in. (15-cm) NPS sch-10. The calculated LHe flow rate, using this size pipe and an estimated heat load of 460 W, is more than 350 g/s for each magnet. Corresponding mean vapor quality is less than 4 vol% (0.7% by mass) at the top of the magnet and less than 20 vol% flowing into the Dewar. These values are considered conservative and satisfy our design requirements.

Maximum helium temperatures in the magnet are expected to occur near the helium inlet where hydrostatic pressures are highest. Liquid helium from the Dewar will be 4.35 K, but piping and magnet heat leaks could cause the helium temperature to reach 4.50 K.

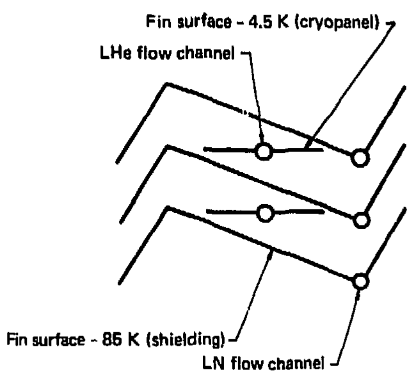

Fig.6 Cryopanel cross section

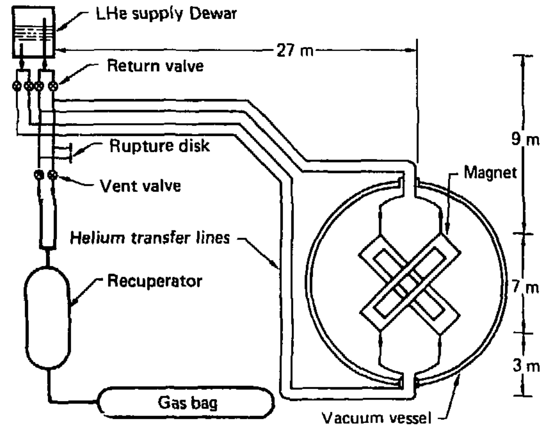

Fig.7 *Schematic of LHe and recovery piping system for the magnets*

The minimum transition temperature of the superconductor in the MFTF magnet is 5.0 K, resulting in a 0.5 K difference for heat transfer. Cryostability studies indicate this is acceptable.

A plenum is included at the top and bottom of each coil near the supply and outlet ports, as illustrated in Fig. 8. These plenums are 6-cm thick and constructed of 6.5-mm-thick layers of fiberglass-epoxy composite having 5- by 37-mm slots alternately oriented 90 deg to each other. They provide a 50% bearing surface for the conductor and a 0.5 porosity for

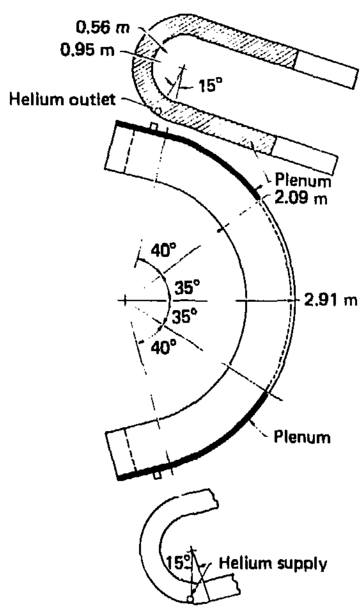

Fig.8 Magnet coil jacket showing dimensions and locations of helium plenums

helium flow. Both plenums distribute flow entering and leaving the coil, and the top plenum also allows vapor to flow outside the coil so the conductor will always be liquid-cooled. The overall porosity of the coil is approximately 0.32, and the estimated hydraulic diameter for LHe flow is 3.2 mm. The conductor is cooled to less than 4.5 K by LHe pool boiling and natural convection through the coil.

External surfaces of the magnets will be shielded by more than 312 m^2 of LN-cooled panels. Radiation barriers would ordinarily be installed between the LN panels and magnets, but since the panels will also serve as a heat source for periodic regeneration (evaporation of condensed hydrogen) of the magnet surfaces, the barriers are excluded. However, combined radiation and conduction heat transfer from the LN panels to each magnet is estimated to be less than 100 W.

The magnets will be supported by two hanger and five stabilizer struts attached to the vacuum vessel (Fig. 9). Intermagnet supports connect the two magnets through their external case. The stainless steel struts and LN-cooled sections at optimum locations will minimize heat conduction. Also, LN-cooled radiation shields will be wrapped around each strut. Heat transfer to each magnet from the struts is estimated to be approximately 30 W.

Liquid nitrogen panels facing the plasma fan or neutral beams will be protected by water-cooled panels. These water-cooled panels will absorb up to 1 MW/m^2 from the plasma and up to 10 MW/m^2 from neutral-beam heating. The panels will also serve as a substrate for 100 m^2 of fresh titanium getter film that will be deposited on the panels before each experiment.

The mean steady-state heat transfer rate to the magnet coil from external sources will be approximately 4 W/m^2 of coil bundle surface or 168 W/magnet, resulting in 0.11 cm^3/s of helium vapor generation per m^2 or 4.6 cm^3/s in each magnet. This vapor will percolate to vapor plenums, thus keeping the superconductor flooded with LHe.

Up to 10 d will be required to achieve cool down of the magnets from room temperature to 4.5 K. The minimum allowed time to prevent unacceptable thermal stresses is 3 d. Warm-up can be achieved in approximately 5 d.

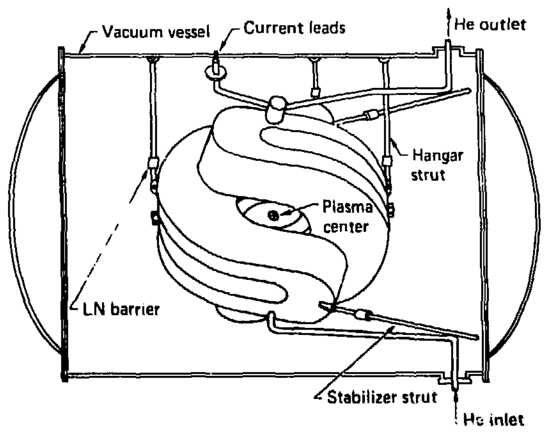

Fig.9 Magnets in the vacuum vessel showing the LHe lines, support struts, and current leads

MAGNET RECOVERY SYSTEM

If the magnet should experience a quench (i.e. ceases to operate in its superconducting mode), a large amount of helium vapor would be generated by Joule heating. Most of the stored energy will be dissipated in an external dump resistor, but the remainder will be converted to sensible heating of the magnet and phase change of LHe. When this occurs, the return- and vent-line valves will be actuated by an automatic detection system so that the magnet Dewar will be isolated from the magnet system and the vapor will vent to a recovery system. Should an overpressure occur, rupture disks shown in Fig. 7 will open at 80 psi (550 kPa) to protect the piping system.

The recovery system includes a 9-m^3 recuperator and a 3000-m^3 helium gas bag. The recuperator warms the vented helium enough to protect the gas bag from thermal shock. The recuperator is a 2.1-m-diameter, 2.4-m-long vessel filled with 45,000 kg of 2.5-cm-diameter steel spheres, and the maximum helium flow rate through it is approximately 16 kg/s. The gas bag is a 37 × 9 × 7.3-m neoprene pillow and collects only one-half of the maximum volume of gaseous helium vented during a quench.

Another source of gaseous helium that flows into the recovery system is the magnet current leads. The two lead pairs make a transition from LHe to room temperature at the vacuum vessel wall penetration. They are vapor-cooled at this location to minimize heat flow into the LHe system. The helium vent rate at rated current (6000 A) through the leads is 1.6 g/s for the two pairs.

FUTURE SYSTEMS

Design studies of a larger MFTF (designated MFTF-B) are currently in progress. The enlarged facility, if constructed, will have a LHe system of almost 10 kW refrigeration and a 1800 L/h liquefaction rate. The LHe will be used to cool 1800 m^2 of cryopumping panels and 22 large superconducting magnets contained in a 64-m-long vacuum chamber. Scheduled completion is mid-1983. The project will be a major step toward realization of a tandem mirror fusion reactor for production of electrical power.

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